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Three-dimensional hydrodynamic modelling in a bay of the Lake Mälaren to assess environmental impacts from a cooling and heating power plant production

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Abstract— The power production company Norrenergi owns a power plant in Solna, Stockholm county, Sweden, to produce heating or cooling energy by exploiting intake water's temperature. In its current configuration, the power plant is connected to the network of the Bromma sewage treatment plant, located in the northern part of Stockholm and uses this water for production. The planned commissioning of a new sewage treatment plant in Henriksdal in the southern part of the city, thought to replace the Bromma sewage treatment plant, will lead the current sewage network used by Norrenergi's power plant to be decommissioned. In order to maintain water supply for its power plant, Norrenergi is now seeking environmental permit to use water from the Bällstaviken bay in Solna where the old intake and outlet structures exist. This article presents the hydrodynamical modelling performed as part of the environmental permit application. The work has focused on describing the thermal dispersion conditions for an extreme energy demand in the summer (cooling production), where the released water temperature is increased between 5.5 and 10.0 °C during a daily cycle. Hydrodynamic modelling has been performed with the software TELEMAC-3D version 7.3. The first part of the modelling work has been to perform flow measurements in order to calibrate the model with respect to currents. Some preliminary dispersion tests showed that in their current configuration, the current intake and outlet structures, both located in the Bällstaviken bay, do not offer optimal production capacity due to a very high risk for a temperature shortcut. To mitigate this risk, a new location for the inlet has been investigated. A location in the adjacent Ulvsundasjön bay has been chosen which offers the possibility to take water from a greater depth with a cooler temperature especially during summer months, making it possible to reduce the relative temperature difference between the intake and outlet depths, hence lowering the environmental impacts. The thermal dispersion modelling has been performed for this intake configuration for several representative wind speeds and directions. The results show that the water temperature in the Bällstaviken bay is significantly increased due to its relatively small volume whereas impacts are, as expected, lower in the adjacent Ulvsundasjön bay which has a greater volume. The results also show a clear influence of wind direction on thermal dispersion conditions. The environmental risk assessment shows that the planned production is not expected to significantly alter

the flora and fauna in the study area mainly due its current low ecological status.

I. INTRODUCTION

The power production company Norrenergi owns a power plant in Solna, Stockholm county, Sweden, to produce heating or cooling energy by exploiting intake water's temperature. To be able to continue its production, the power plant needs to use new source of water and is now seeking environmental permit to use water from the Bällstaviken bay in Solna where old intake and outlet structures exist. In the first section, an overview of the study area and of the power plant characteristics are presented. In the second section, the three-dimensional hydrodynamic model developed for the study is detailed. The article then focuses on the model calibration based on field measurements and the identification of key model parameters that have been used in all the simulations. Finally, a quick overview of the design thermal dispersion simulations is given with the related environmental impacts.

II. PRESENTATION OF THE STUDY AREA

A. Location and environment

The work presented in this paper concerns flow simulations in the bays of Bällstaviken and Ulvsundasjön located in the western part of the city of Stockholm, Sweden (see Fig. 1). Those two bays are part of the Lake Mälaren that flows into the Baltic Sea at several outlet points, the main one being around the Old Town island in the centre of Stockholm. The two bays receive water from a natural catchment drained by the Bällstaå River (38.9 km² with a mean annual discharge of approx. 0.3 m³/s) and from relatively small urban catchments. Bällstaviken is the smallest bay characterized by a water depth between 2 and 6 m whereas Ulvsundasjön covers a larger area and is significantly deeper (up to 15 m). Ulvsundasjön is connected to other bays in the eastern part of Lake Mälaren via two passages, the main one being located in the southern part of the study area. Environmental studies have characterized Bällstaviken and Ulvsundasjön bays' ecological status as low due to the presence of polluted sediments in harbours and the lack of important species (fauna and flora).



Figure 1: Location of the study area with a regional map (top) and the location of the Bällstaviken and Ulvsundasjön bays in the center of Stockholm (bottom). Bays are located inside the red polygons.

B. Stratification

The bays of Bällstaviken and Ulvsundasjön present a stratification due to temperature gradients during the summer season (June to September). The stratification is more clearly marked in Ulvsundasjön (Fig. 2) than in Bällstaviken due to the limited water depth of the latter bay. During the rest of the year, the temperature gradients are minimal and therefore stratification is limited and is considered as negligible.

C. Power plant

In its actual configuration, the power plant is taking water from the Bromma sewage treatment plant and releasing it into the Baltic Sea via a tunnel network. As the Bromma plant will be decommissioned, Norrenergi is willing to use water from the bays of Bällstaviken and Ulvsundasjön for energy production. This alternative is motivated by the existing old intake and outlet structures, located in the Bällstaviken bay, and could be reused without undertaking major refurbishment works.

Norrenergi is planning to increase energy production capacity for the plant with a maximal capacity of 105 MW. As

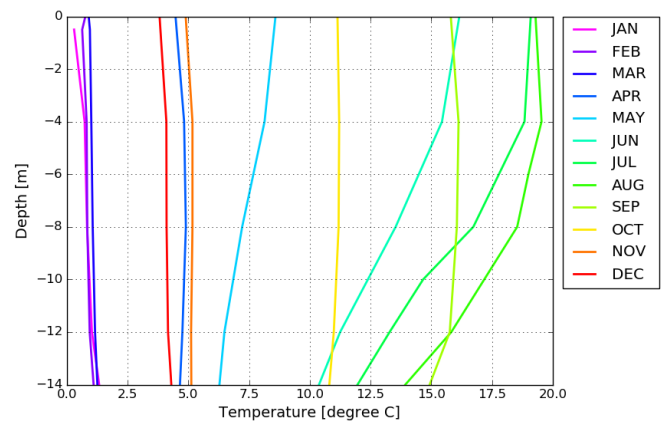


Figure 2: Monthly average of water temperature in Ulvsundasjön bay.

environmental impacts during the winter period (heating production, release of cooled water) are negligible, the project has been focused on assessing the expected thermal status of the bays during the summer period (cooling production, release of heated water) for a predefined design production sequence characterized by a constant water discharge (inflow and outflow) of $2.5 \text{ m}^3/\text{s}$ and by a temperature increase in the outflow varying between $+5.5$ and $+10.0 \text{ }^\circ\text{C}$, depending on the time of the day, compared to the reference water temperature at the intake. This design sequence has a duration of one week and is illustrated on Fig. 3.

The first dispersion simulations performed with the existing intake and outlet showed that the configuration of those structures was not appropriated for summer production as the intake is located too close to and higher than the outlet, pumping high amount of heated, less dense, water and hence dramatically reducing production capacity. It has then been decided to relocate the intake to a deeper part of the system. The point chosen is located approximately 1 km east of the outlet, in a region where the water depth is approximately 13 m, i.e. 9 m below the outlet level (see Fig. 4). This new location offers a natural advantage during the summer period when a strong temperature gradient is present between the

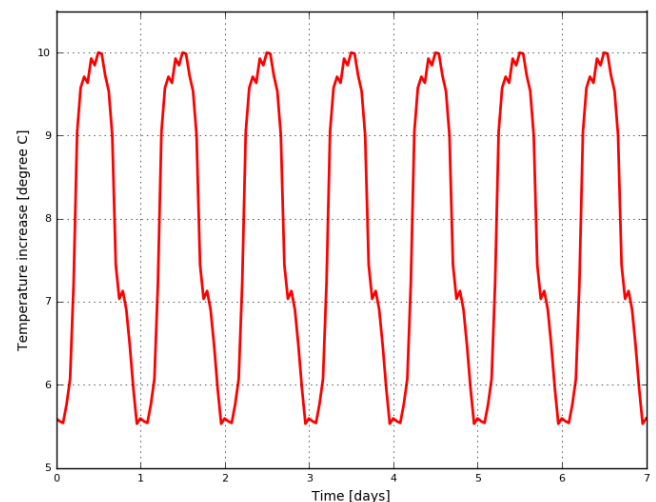


Figure 3: Design production sequence for outfall of heated water. Constant discharge of $2.5 \text{ m}^3/\text{s}$.

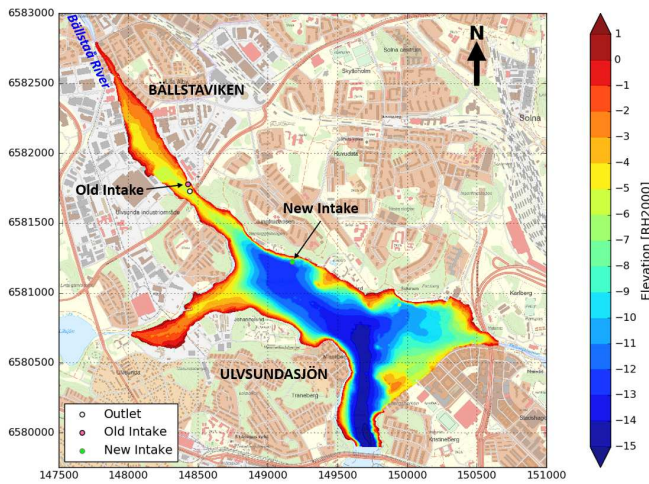


Figure 4: Model domain and bathymetry, location of the intakes and outlet structures. Coordinates for all maps are expressed in SWEREF 99 1800 (m).

water surface and the bottom, thus making it possible to reduce the environmental impacts with regards to the release of heated water and its dispersion near the water surface.

III. PRESENTATION OF THE TELEMAC-3D MODEL

A. Model domain and bathymetry

The model domain covers the bays of Bällstaviken and Ulvsundasjön in their entirety over a surface of approx. 1.4 km², see Fig. 4. A multibeam scanning from a recent bathymetrical survey was used to define bottom levels within the model.

B. Computational mesh

The computational domain is composed of a two-dimensional horizontal unstructured triangular mesh that has been duplicated 22 times along the vertical at fixed elevations to create a three-dimensional mesh. The lowest plane describes the bathymetry and the highest plane corresponds to the computed water surface. The two-dimensional horizontal mesh was created with BlueKenue and contains approx. 124,000 elements while the three-dimensional mesh contains approx. 2,600,000 elements. The mesh size in the horizontal plane is of approximately 5 m in the whole domain. The distance between the vertical planes is varying from 0.1 m at the free surface, 0.5 m down to 7 m deep, 1.0 m down to 10 m deep and 2.0 m below this level.

C. Initial and boundary conditions

A water temperature profile corresponding to the July month (see Fig. 2) has been defined as initial conditions. The water temperature at the free surface is 19.0 °C.

The hydrodynamic model has three open boundaries. In the Bällstaviken bay, an inflow boundary has been applied to model the inflows from the Bällstaå River. Prescribed discharges correspond to monthly average flow rates. In the Ulvsundasjön bay, two water level boundaries have been defined where the bay is connected to other parts of the Lake Mälaren. The prescribed water level at those boundaries corresponds to the mean (and regulated) water level for Lake Mälaren, +0.86 m in height reference system RH2000.

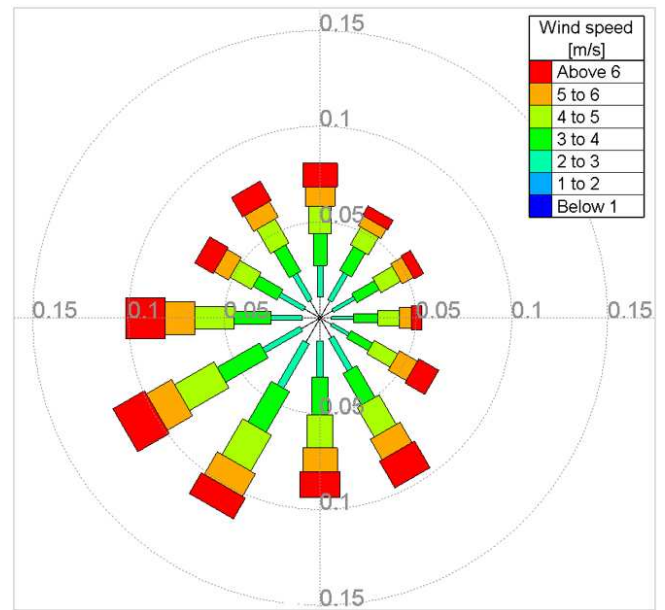


Figure 5: Wind rose from Bromma airport, period April to September.

Wind has been applied as a boundary condition at the water surface based on mean wind speeds for several representative wind directions. Mean wind speeds are of approximately 4 m/s according to the wind rose from the station of Bromma airport (time-series with 80 years of data) located less than one kilometre away from the model area, see Fig. 5.

Inflow and outflow to and from the power plant has been modelled with sink/source points using a constant flow rate of 2.5 m³/s. The intake has been conservatively placed at a depth of 7 m, to ensure that the reference intake temperature was not underestimated (important regarding environmental impacts). The outlet has been modelled with two source points as the structure ends with a box with two lateral openings in order to dissipate energy and increase mixing. Hence, the source points were defined without momentum. Water temperature at the outlet has been prescribed according to the design sequence presented in Fig. 3. The actual water temperature at outlet has been defined between 22.8 and 27.3 °C (i.e. between 5.5 and 10.0 °C warmer than the water temperature at intake depth, 17.3 °C, for an average July month).

D. Numerical settings

Water temperature has been defined as an active tracer to take buoyancy effects into account, and water density being computed as a function of water temperature using Eq. 1 [1,2].

$$\rho = \rho_{ref} \left[1 - 10^{-6} \cdot T(T - T_{ref})^2 \right] \quad (1)$$

Where ρ is the water density [kg/m³], ρ_{ref} is the reference water density at $T_{ref} = 4$ °C (999.972 kg/m³) and T is the actual water temperature [°C].

Bottom friction was modelled using Nikuradse formulation with an equivalent sand roughness coefficient of $k_s = 0.02$ m.

The hydrodynamic model has been run with TELEMAC-3D (version 7.3) in non-hydrostatic mode with a time-step of

5 seconds. Turbulence has been modelled with the $k-\epsilon$ model in the horizontal plane and with Tsanis' mixing length model in the vertical direction (see section Calibration for more details). The advection scheme chosen for velocities, $k-\epsilon$ and tracers is the explicit MURD scheme without tidal flats treatment. The model has been run on the Beskow computer at the PDC Center for High Performance Computing at the KTH Royal Institute of Technology, Stockholm.

E. Limitations

The hydrodynamic model has not been coupled with the atmospheric processes available in the WAQTEL module due to the lack of calibration data. One of the consequences is that the stratification profile could not be kept over long simulation periods, which would make the interpretation of the model results challenging with respect to the water temperature increase during the release period. It can be noted that tests were performed with the more computationally expensive MURD 2nd order and LIPS advection schemes. Although allowing a reduction of the numerical diffusion, the stratification was still altered during the simulation. To avoid having this issue, the model was run with a uniform initial water temperature equal to the surface temperature (19.0 °C). Tests showed that this simplification has minor incidence on the dispersion conditions as the water density difference between released water and ambient water at outlet depth is approximately 10 times greater than the water density difference between intake and outlet depths.

Another consequence is that the energy exchanges between the water system and the atmosphere are not taken into account (solar radiation during day time, evapotranspiration and convection during night time). The energy gained through solar radiation is independent of the actual water temperature (i.e. identical during or outside release periods) whereas the energy loss through evapotranspiration and convection is function of the temperature difference between water and atmosphere (i.e. greater energy loss during periods with release of heated water). Hence, not taking into account those processes can be considered conservative regarding thermal dispersion as the temperature cooling occurring during night time is discarded.

IV. CALIBRATION

A. Field measurements

Field measurements have been performed within the study area in order to acquire calibration data for the hydrodynamic model. Field measurements consisted of:

- Current velocity and direction as well as water temperature between bottom and water surface at one point.
- Wind velocity and direction as well as other meteorological parameters (air temperature, atmospheric pressure, precipitation) and water level variations at one point.

Measurements covered a period of one month and 10 days, between 2018-09-20 and 2018-10-31. Current measurements have been performed with an Acoustic Doppler Current

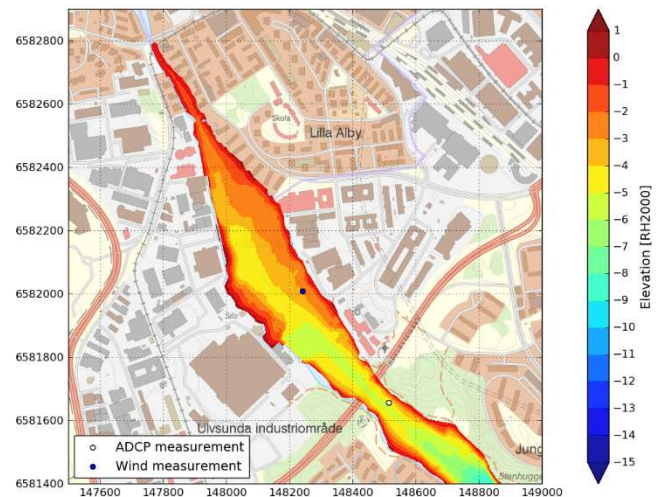


Figure 6: Location of field measurements.

Profiler (RDI/Teledyne Sentinel Workhorse 600 kHz ADCP). Due to budget constraints, only one ADCP has been used. It was then chosen to place the equipment at a relevant location regarding current circulation within the study area. As the volume of the Bällstaviken bay is small, water exchanges with the Ulvsundasjön bay should be modelled in a correct way in order to ensure a correct modelling of the water system and associated environmental impacts. The ADCP has then been located in the sound between the two bays in a location where the water depth was approximately 5.5 m (see Fig. 6). The flow data consist of time-averaged values over a 15-minute period in eight 0.5 m-high measurement cells located between the bottom and the water surface. The standard deviation regarding this measurement set-up was of 0.0144 m/s. This value, quite large compared with the expected current velocities, was the result of a compromise between the number of cells and their size in the vertical direction due to the relatively small water depth at this location.

The weather station used for wind speed and direction and meteorological parameters was, for practical reasons, located on a pier owned by Norrenergi in Bällstaviken bay, approximately 450 m northwest of the ADCP location (see Fig. 6). The measured wind speeds have been corrected from a height above ground in order to obtain values at a 10 m height reference using a classical logarithmic profile.

Water temperature measurements showed only small differences in the vertical direction, which was an expected result being given the period during which the measurements were performed (see Fig. 2). Consequently, no temperature stratification was defined in the hydrodynamic model for the calibration step. Water level measurements have been used as boundary conditions for the two southern open boundaries. Inflow rates from the Bällstaå River were not available. The model was run assuming an average monthly discharge for October of 0.256 m³/s.

B. Calibration case

The model calibration has been performed over a duration of seven days taken from the global measurement period. The period chosen, 2018-10-07 to 2018-10-14, shows mainly W-

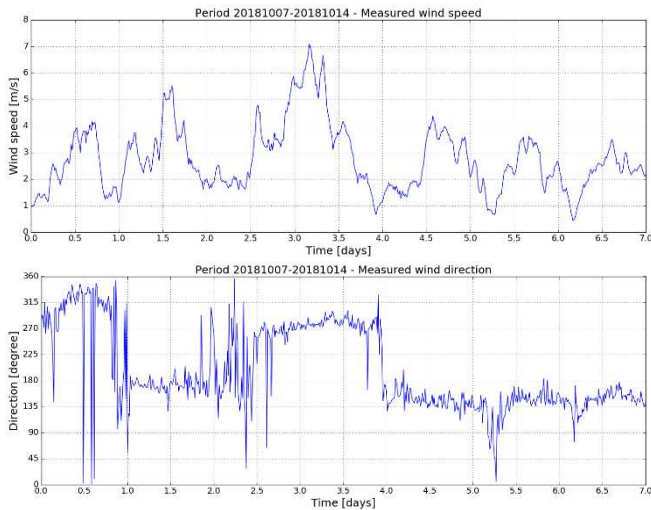


Figure 7: Measured wind speed (top) and direction (bottom) for the calibration period.

NW and SE-S winds with speeds ranging from 1 to 7 m/s. Wind directions correspond to those having the largest impact on dispersion conditions within the study area (see Fig. 7).

The initial model set-up consisted of the following features:

- Mesh size in horizontal direction: approx. 5 m.
- Vertical mesh spacing below water surface: 0.2 m.
- Turbulence model in horizontal and vertical directions: k-ε.
- Time-step: 5 s.
- Non-hydrostatic version.
- MURD scheme without tidal flats.

The mesh size in the horizontal direction and time-step were defined after preliminary tests through an iterative process in order to remove instabilities. These parameters as well as the MURD scheme and TELEMAC-3D's non-hydrostatic version have been used in all calibration runs.

The first results using the set-up described above showed very large differences with the flow measurements, with the highest simulated surface currents of about 0.05 m/s while 0.30 to 0.45 m/s was measured, as well as some discrepancy regarding current direction. The two main reasons to explain these differences are:

- Topographical effects acting on local wind speed and direction.
- Turbulence model in the vertical direction.

Experience on local wind climate indicates that NW and SE winds are concentrated below the bridge in the sound, creating a wind acceleration and a deviation of its direction. Unfortunately, this effect is not accounted for in the measurements as the weather station was placed at an undisturbed location. The large influence of this topographical effect could be estimated by comparing expected surface

currents for the maximal measured wind speeds based on Wu [3] cited in TELEMAC-3D's validation manual [4] in which surface current can be estimated with Eq. 2.

$$U_s = 0.55\sqrt{\tau_w/\rho_{air}} \quad (2)$$

Where U_s is the surface wind-generated current [m/s], τ_w is the wind shear applied to the free surface [Pa] and ρ_{air} is the air density (typically 1.23 kg/m³ at 15 °C). The wind shear τ_w can be calculated according to the methods provided in [1]. Fig. 8 illustrates how the surface currents U_s varies with respect to wind speed. Surface currents in the range of 0.30 to 0.45 m/s are expected to be generated by wind speeds ranging between approximately 13 to 17 m/s, which are significantly larger than the measured undisturbed wind speeds during the calibration period (3-7 m/s).

In order to account for this topographical effect, a spatially varying correcting factor has been applied on both wind speed and direction by altering the subroutine `meteo.f`. The

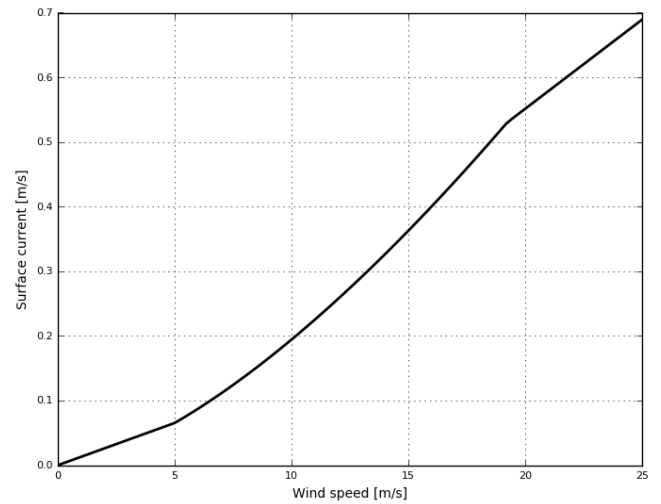


Figure 8: Estimated surface current as function of wind speed (Eq. 2).

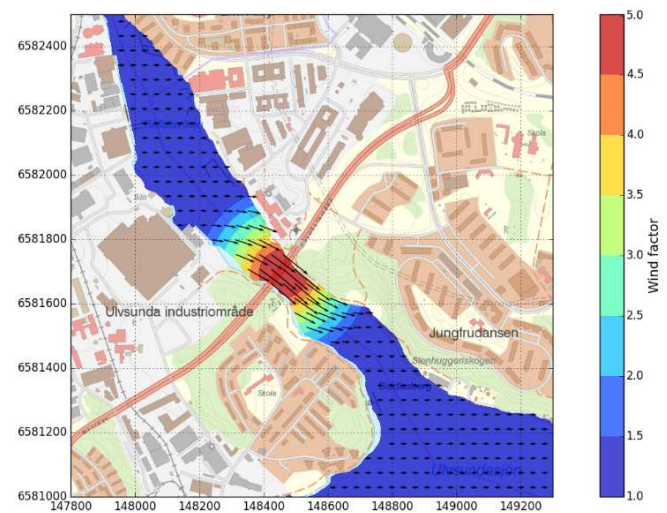


Figure 9: Wind correction factor on wind speed and wind direction. Example for a westerly (270°) wind.

correcting factor is applied to winds from sectors W-NW-N and E-SE-S, i.e. winds converging into the sound. The correction factor is applied linearly on wind speeds and directions from about 300 m downstream/upstream of the sound's center as depicted on Fig. 9. Several wind factor values have been tested, best results were obtained for a value of 5 which seems reasonable compared with the simple comparison detailed above.

Results from a simulation performed with the initial set-up and with the wind correction factor showed an improvement but still lower simulated values compared to surface current measurements, see Fig. 10.

Changing the turbulence model in the vertical direction from $k-\epsilon$ to Tسانيس' mixing length model together with a refinement over the vertical just below free surface (0.1 m as recommended in [4]) yielded a good agreement between

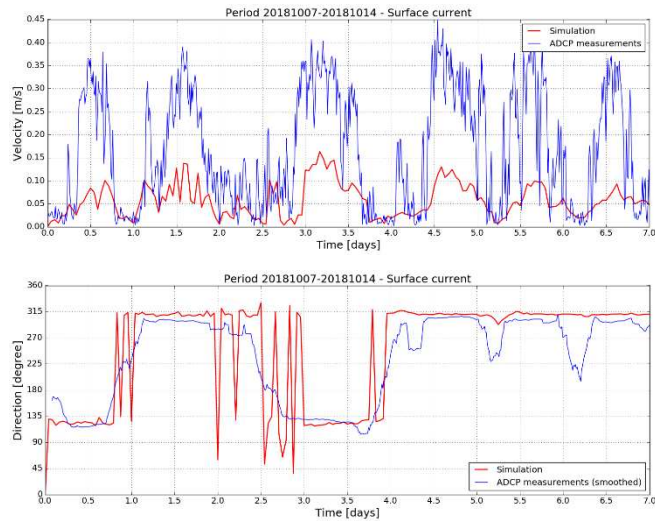


Figure 10: Calibration case, surface current velocity (top) and direction (bottom) with $k-\epsilon$ turbulence model in all directions and with applied wind correction factor.

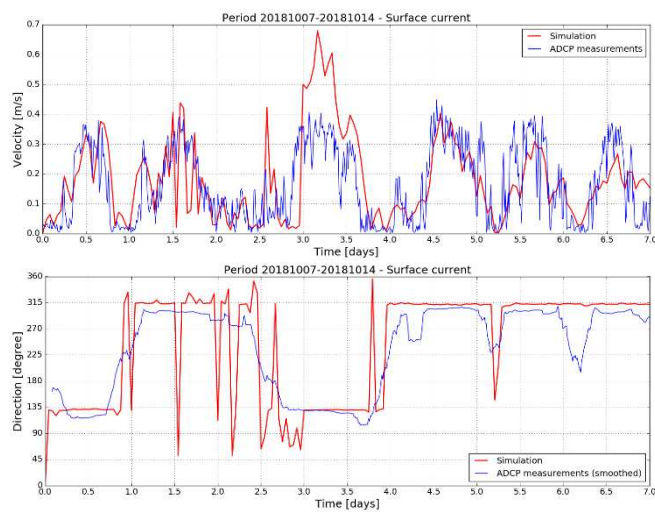


Figure 11: Calibration case, surface current velocity (top) and direction (bottom) with $k-\epsilon$ turbulence model in horizontal direction, Tsanis' mixing length model in vertical direction, plane located 0.1 m below the water surface and with applied wind correction factor.

model results and field measurements, see Fig. 11. It can however be noted that the model overestimates the wind speed around day 3, where measured wind speeds were up to 7 m/s from SE. This difference can be due to the assumption of a linearly varying wind correction factor even for high wind speeds whereas the natural acceleration probably converges to a lower value above a given threshold speed. Surface current directions are also reproduced in a correct way. The rapid variations obtained from the model occur during periods when the wind directions are at the border of the considered range for the applied correction and should therefore be interpreted as artificial features without impact on the flow conditions for the design simulations. In Ulvsundaşjön bay, i.e. outside of the sound where wind driven currents can develop over a sufficiently long fetch, the obtained surface currents are in good agreement with the estimated values based on Eq. 2.

The differences obtained on surface current velocities between $k-\epsilon$ and Tsanis model are significant. With $k-\epsilon$ and unlike classic mixing length models like Tsanis', the turbulent kinetic energy k at free surface, and indirectly the turbulent viscosity, is computed based on the local wind friction velocity [1]. Comparison between these two types of turbulence models on a simple channel test case with wind-driven currents shows very different viscosity patterns at the free surface, with higher viscosities and consequently lower velocities computed by $k-\epsilon$ compared with Tsanis. The exact cause of these differences has not been investigated but the method used to compute k , together with the isotropy assumption and strong mesh distortion are likely to have an influence on those results.

Comparison between the model and the measurements between the bottom and free surface did not show a good agreement. Measured current velocities are ranging between approximately 0.01 and 0.04 m/s which means that the quality of the measurements is expected to be significantly affected by their precision (standard deviation of 0.0144 m/s). The results from the model are generally lower current

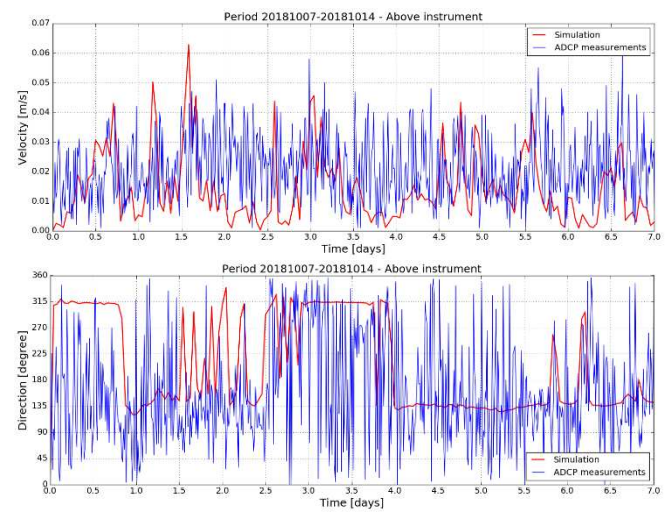


Figure 12: Calibration case, bottom current velocity (top) and direction (bottom) with $k-\epsilon$ turbulence model in horizontal direction, Tsanis' mixing length model in vertical direction, plane located 0.1 m below the water surface and with applied wind correction factor.

velocities excepted during high wind speed periods and bottom current direction in opposite direction from the surface current, as expected, see Fig. 12.

Model calibration has however been considered satisfactory as it is essentially surface current conditions that are of relevance for the study of temperature dispersion. All design model runs have been performed with Tsanis' mixing length model in the vertical direction together with a plane located 0.1 m below the free surface.

C. Validation case

The model validation has been performed over a duration of seven days between 2018-09-28 and 2018-10-05 taken from the global measurement period with mainly W-NW and SE-S winds with speeds ranging from 1 to 6 m/s, see Fig. 13. Due to the uncertainties on the current measurements between

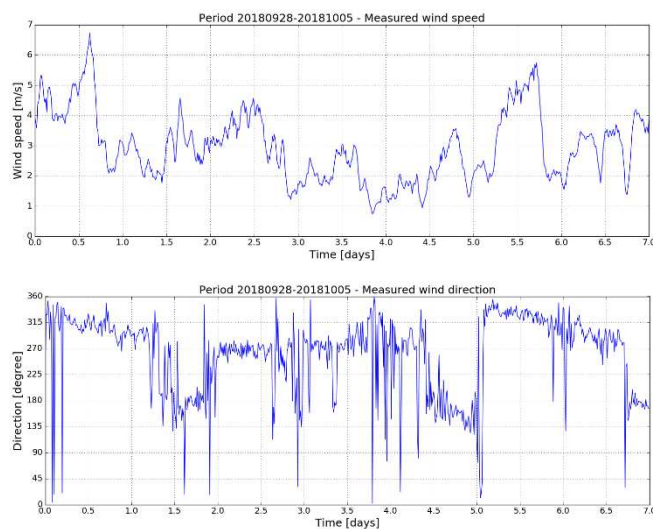


Figure 13: Measured wind speed (top) and direction (bottom) for the validation period.

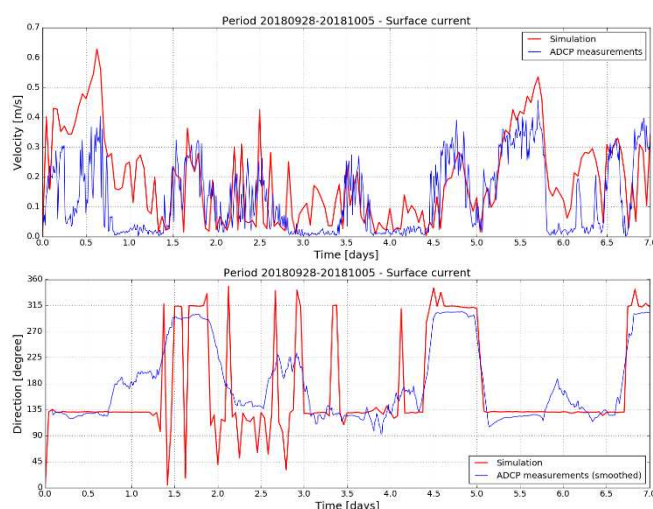


Figure 14: Validation case, surface current velocity (top) and direction (bottom) with $k-\epsilon$ turbulence model in horizontal direction, Tsanis' mixing length model in vertical direction, plane located 0.1 m below the water surface and with applied wind correction factor.

bottom and free surface highlighted in the Calibration case section, only results regarding surface currents are considered.

The model has been run with similar set-up as for the calibration case. Comparison between the model results and the surface current measurements is presented in Fig. 14. Results from the model are in good agreement with the measurements and present similar features as the calibration case with an overestimation of surface current velocities when wind speed becomes larger than approximately 5 m/s and with abrupt current direction changes when undisturbed wind is oscillating around the limits of the direction range considered in the wind correction factor method. The hydrodynamic model is then considered to be validated with respect to surface currents and can be used safely for the range of wind speeds considered in the temperature dispersion study (average wind speeds of about 4 m/s).

V. TEMPERATURE DISPERSION SIMULATIONS

A. Overview of the simulated cases

Dispersion simulations have been performed for four scenarios with different wind directions. In three of these scenarios the wind direction and speed has been kept constant during the whole simulation period (seven days). The corresponding wind directions were the most frequent based on the wind rose from Bromma airport (NW, SE, SW), see Fig. 5, while the simulated wind speeds correspond to each sector's average value (3.5 to 4.1 m/s). The fourth scenario has been defined with a time-varying wind field decomposed into the four main directions (SW, NE, NW, SE) and applied during a similar seven-days period. The wind duration for each sector was based on its occurrence frequency according to the wind rose and using an average wind speed value of 3.8 m/s. The latter scenario features the most realistic dispersion conditions and therefore has been chosen to be described into detail in this article.

The results regarding surface temperature increase at the end of each period for a given wind direction are illustrated in Fig. 15. Temperature values are extracted at two points in the model, one which is representative for Ulvsundasjön bay and the other for Bällstaviken bay, and the results are shown as temperature increase relative to the initial temperature 19.0 °C, see Fig. 16.

As seen from the figures, Bällstaviken bay is affected by a clear increase in temperature of up to 2.5 °C during the first three days with wind from the SW and NE. During days 4 and 5, the temperature reduces by approximately 0.5 °C due to the wind from the NW which enhances the dispersion of the temperature plume towards Ulvsundasjön bay and the downstream boundary Lake Mälaren. Lastly, there is a significant increase in temperature of up to 2.8 °C in both Bällstaviken bay and the northern part of Ulvsundasjön bay with wind from the SW during days 5 to 7.

B. Environmental impacts

In the Swedish environmental quality standards, it states that fish and mussels can be said to not be affected from a discharge of temperate water when the temperature increase is up to 3.0 °C or the water temperature does not exceed 28 °C.

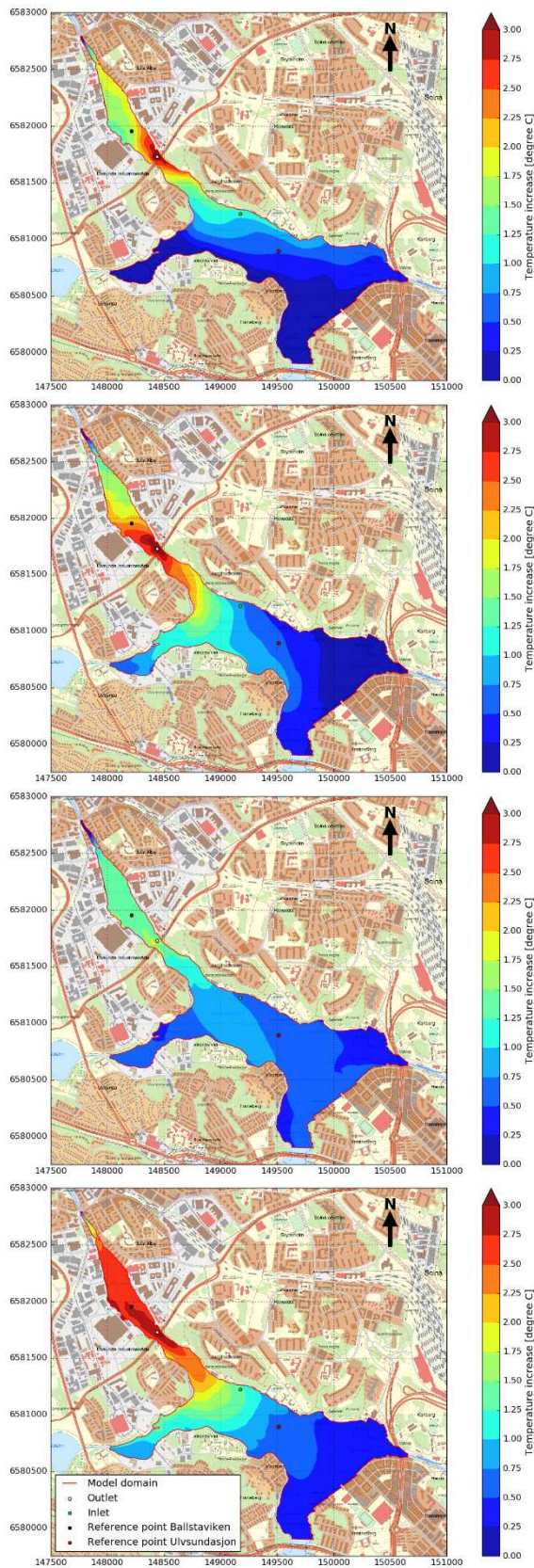


Figure 15: Temperature increase at water surface at the end of each given wind direction period (from top to bottom: SW, NE, NW, SE).

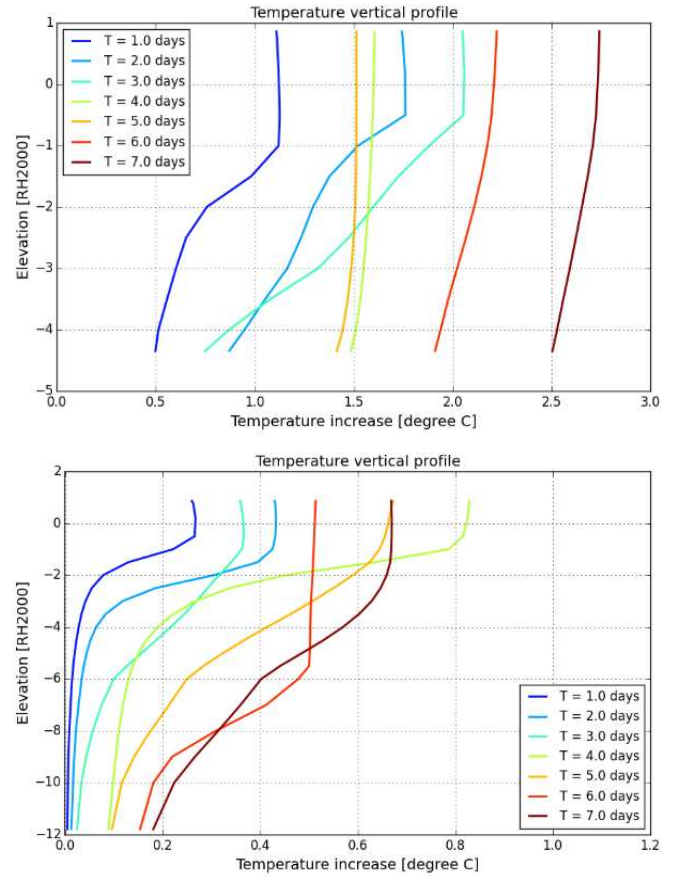


Figure 16: Vertical profiles of temperature increase for Ballstaviken (top) and Ulvsundasjön (bottom) bays. See locations on Fig. 15.

Both Ulvsundasjön and Ballstaviken bays meet this standard according to the results and thus assumed that the environmental impacts on fauna and flow are negligible. Furthermore, the heat pumps have open evaporators which increase the oxygen in the discharge water. This is expected to have a positive impact on the flora and fauna in Ballstaviken and Ulvsundasjön bays.

VI. CONCLUSION

The main findings from the different steps involved in the presented work are as follows:

- The $k-\epsilon$ turbulence model applied in the vertical direction tends to underestimate surface currents generated by wind.
- Tsanis' vertical mixing length model used with discretization of 0.1 m below the free surface provides results in good agreement with theory and field measurements.
- Topography can significantly influence the local wind speed and direction and is therefore an important factor to take into account in hydrodynamic modelling.

- It is necessary to use a coupling between TELEMAC-3D and WAQTEL in order to be able to model stable temperature stratification during long simulation periods and model temperature energy budget more precisely.
- The results from the hydrodynamic model could be used to conservatively estimate the environmental impacts related to the release of heated water in the Bällstaviken and Ulvsundasjön bays.

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performed for Norrenergi as part of the environmental permit regarding the upgrade of the Solna heating and cooling power plant. Field measurements have been performed by the Finnish company Luode Consulting Oy.

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